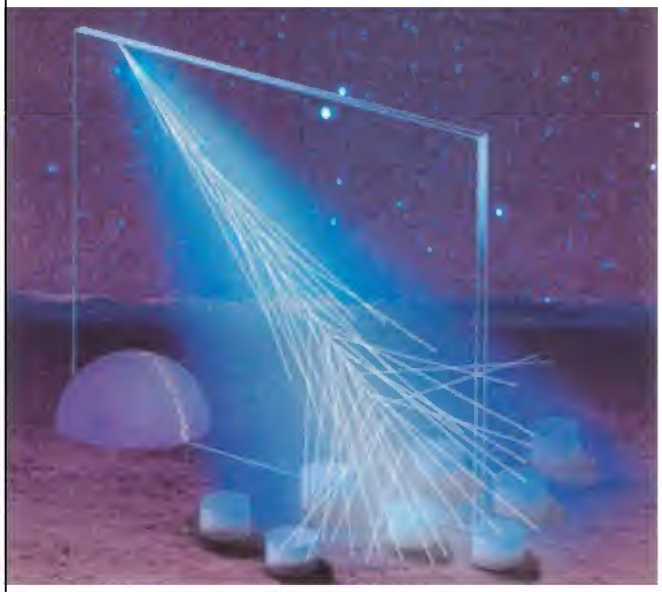
The Gamma Ray Perspective of the Mystery of the Origin of UHECRs

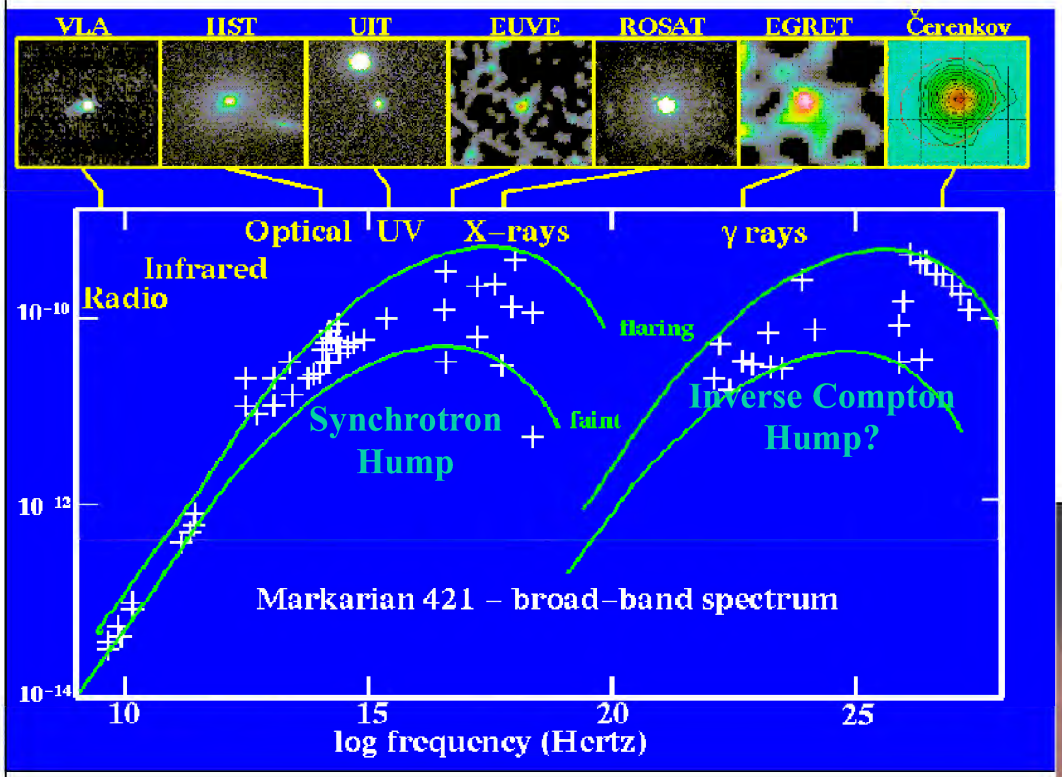
Tonia Venters
Astrophysics Science Division
NASA Goddard Space Flight Center

My Roots...



Pierre Auger (concept)

VHE Gamma Rays in the EBL

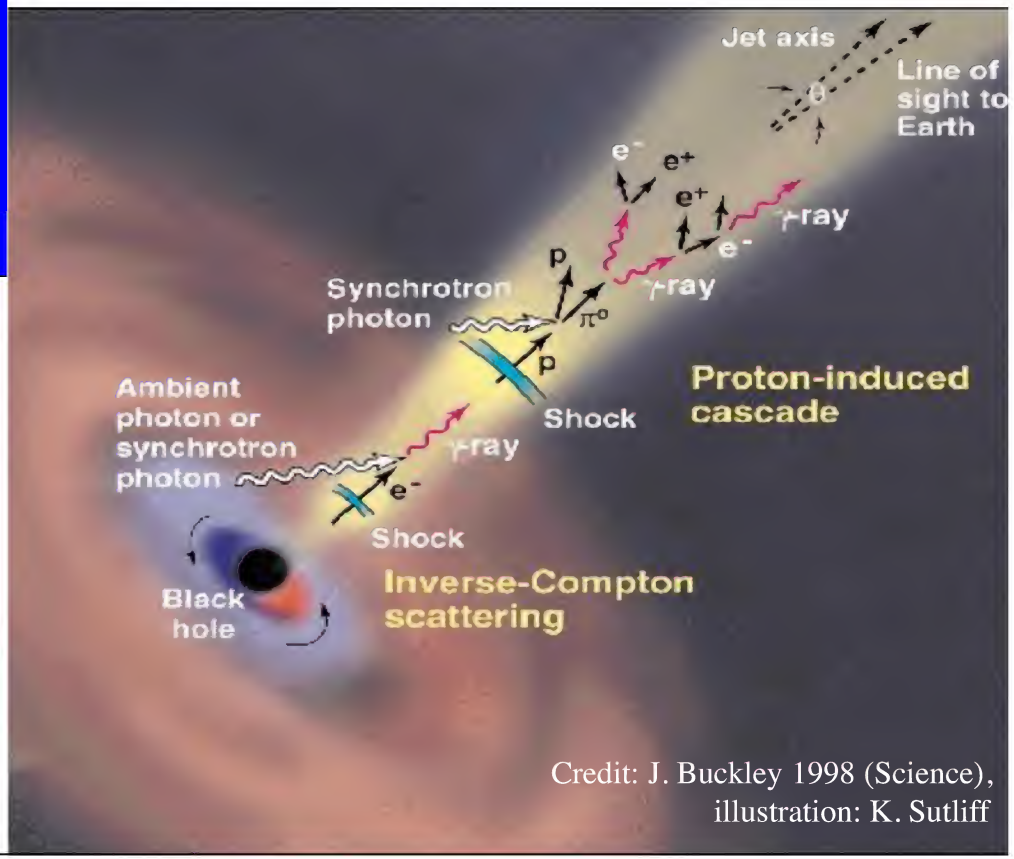


Leptonic - HE hump due to Inverse Compton scattering

- Synchrotron Self-Compton
- External Compton

Hadronic - HE hump due to emission from hadronic interactions

- Photomeson production
- Proton Synchrotron
- Muon Synchrotron



PP Laboratory open questions

- Relativistic jet
- Small angle between jet axis and line-of-sight
- Broadband emission from jet
- Gamma-ray emission: IC of soft photons from energetic electrons
- Very luminous, variable

Connection with Accretion Disk and Black Hole?

$\Gamma \sim 5 \leftrightarrow 50$

Population properties? Evolution?

Effect on host galaxy? Galaxy cluster?

Is radio emission produced in the same location as the gamma-ray emission?

Where in the jet?

Synchrotron? Ambient? From disk? From jet?

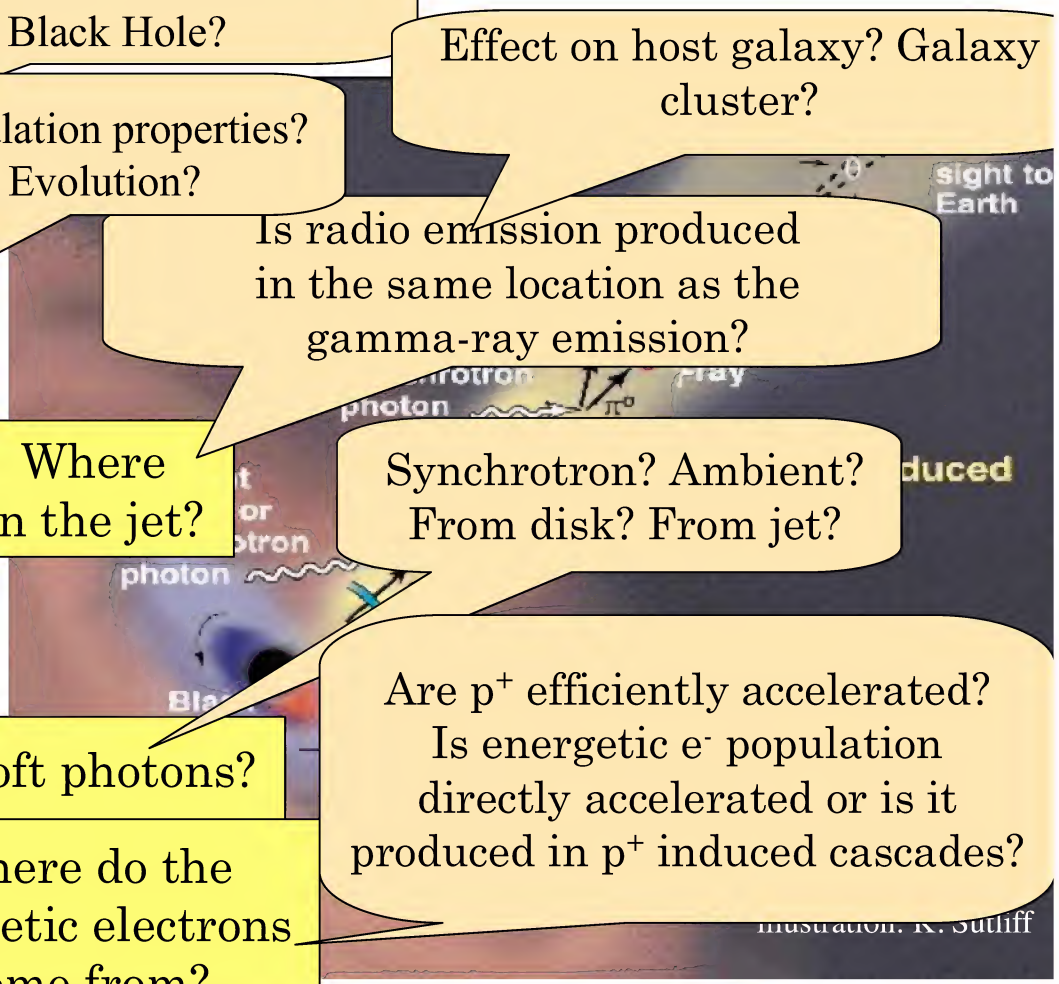
Are p^+ efficiently accelerated? Is energetic e^- population directly accelerated or is it produced in p^+ induced cascades?

Which soft photons?

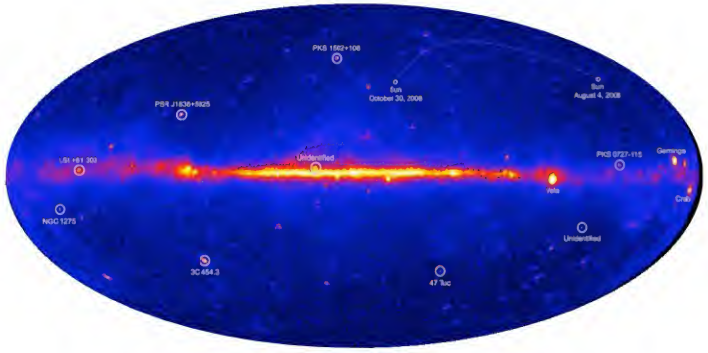
Where do the energetic electrons come from?

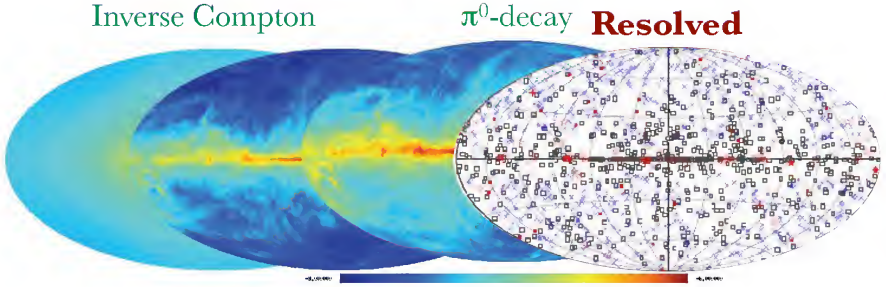
What is the duty cycle of blazars?

Overlap of bursts? Or continuous emission + variability?

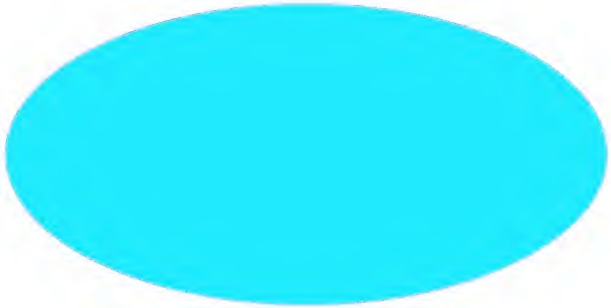


Components of the EGB





Galactic diffuse emission
(CR interactions with the interstellar medium)



Isotropic diffuse emission
(presumably extragalactic)

Known players:

- Star-forming galaxies
- Active galaxies (blazars, and maybe some from other types of radio galaxies)

Suspected contributors:

- Truly diffuse emission - gamma rays produced in EM cascades of highly energetic particles

Players about which we like to speculate:

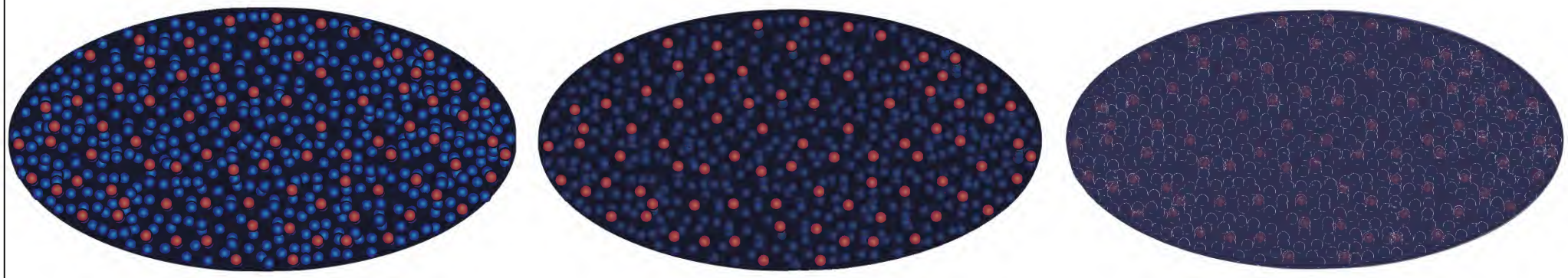
- Exotic physics (e.g., dark matter annihilation?)

Anisotropy of a Multi-component EGB

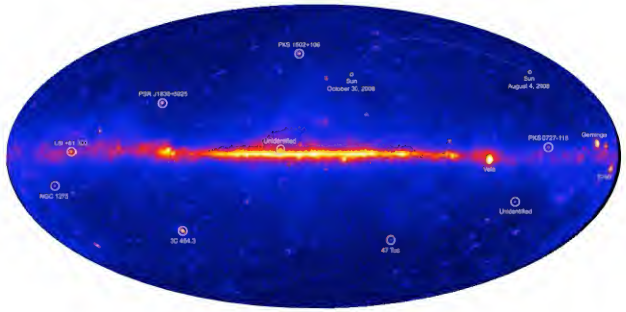
- Determine $C_l(E)$, the angular power of fluctuations in intensity at a given angular scale, l, as a function of energy.
- In a two component background, the anisotropy energy spectrum is given by

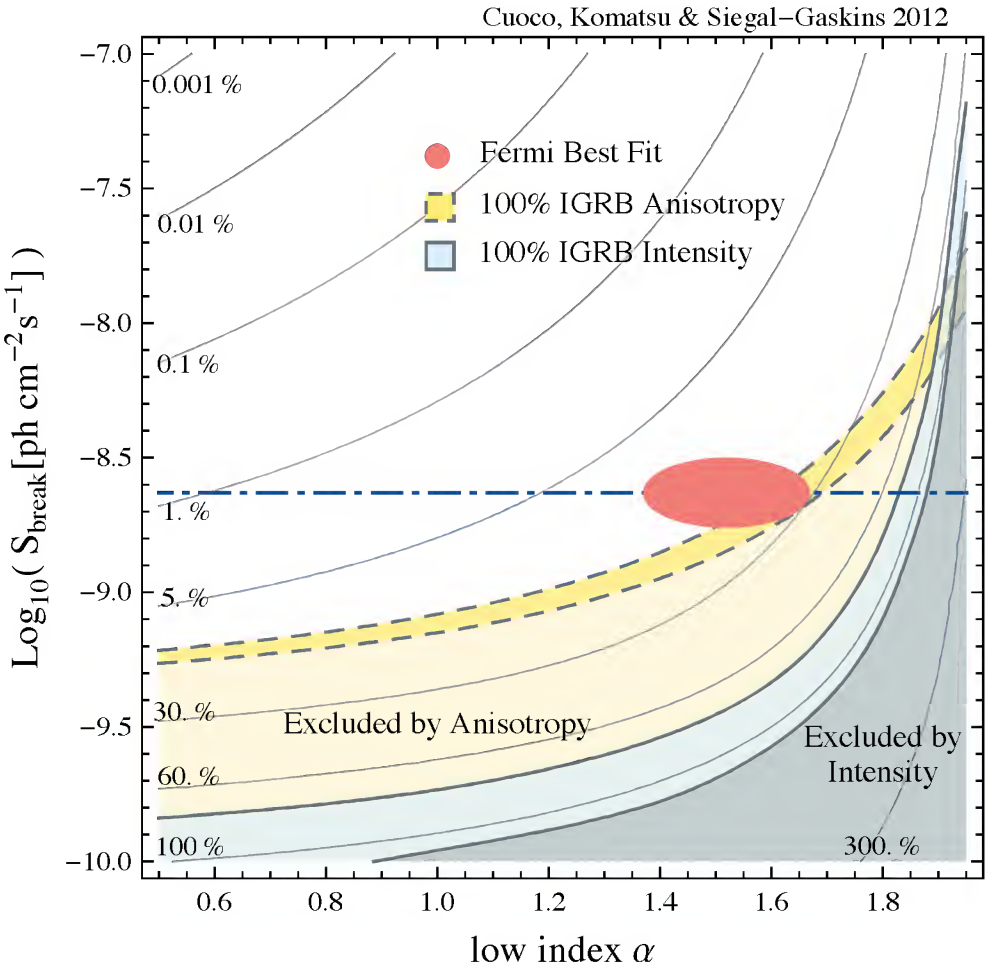
$$C_l^{\text{tot}} = f_1{}^2 C_l^{(1)} + f_2{}^2 C_l^{(2)} + \text{cross terms},$$

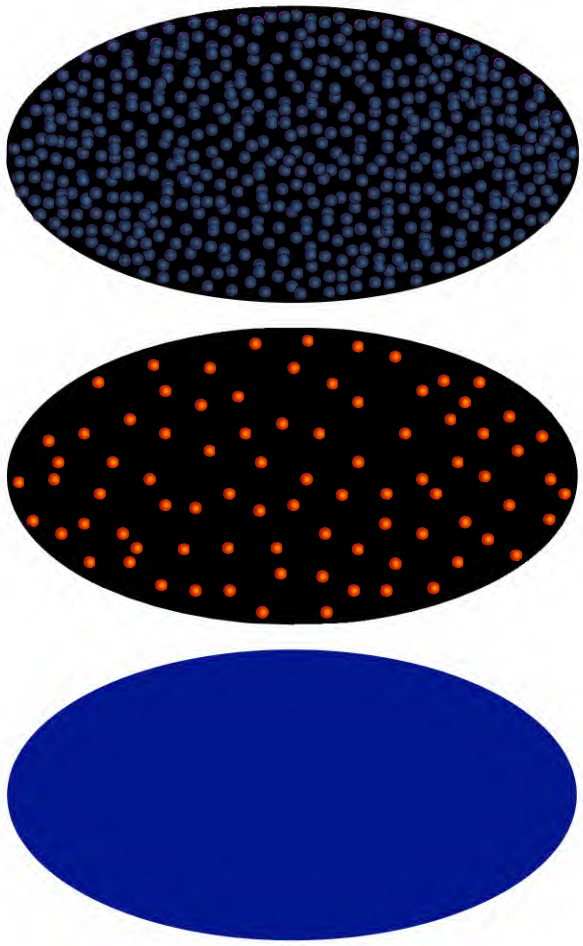
  where f_n is the fractional contribution of component n to the background ($f_n = I_n(E)/I_{\text{tot}}(E)$).
- If the relative contributions of the components of the background change as a function of energy, the result is a *modulation* in the spectrum of the anisotropy as a function of energy.



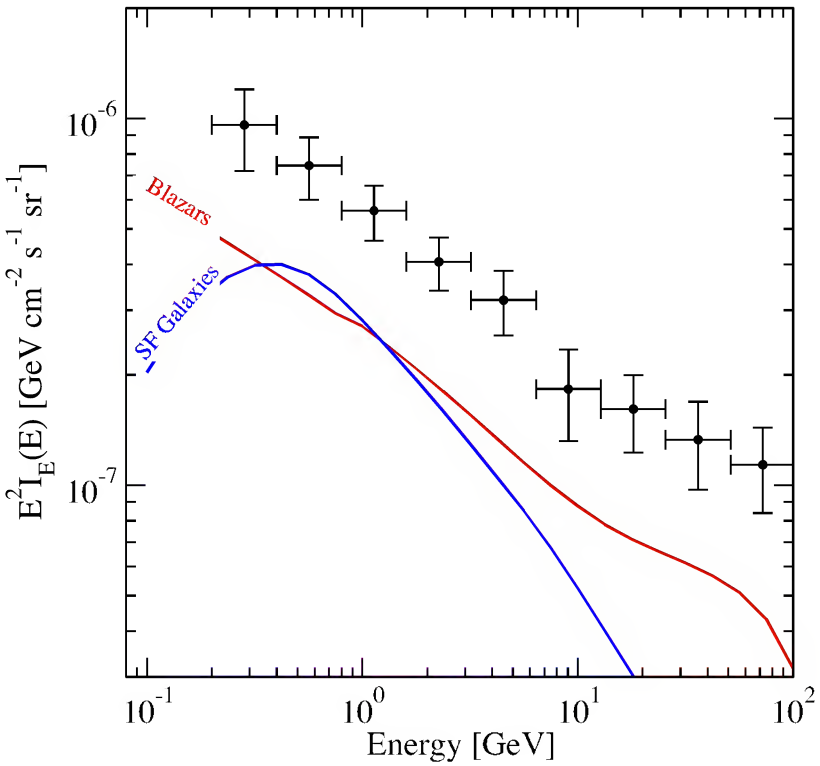
Anisotropy Studies

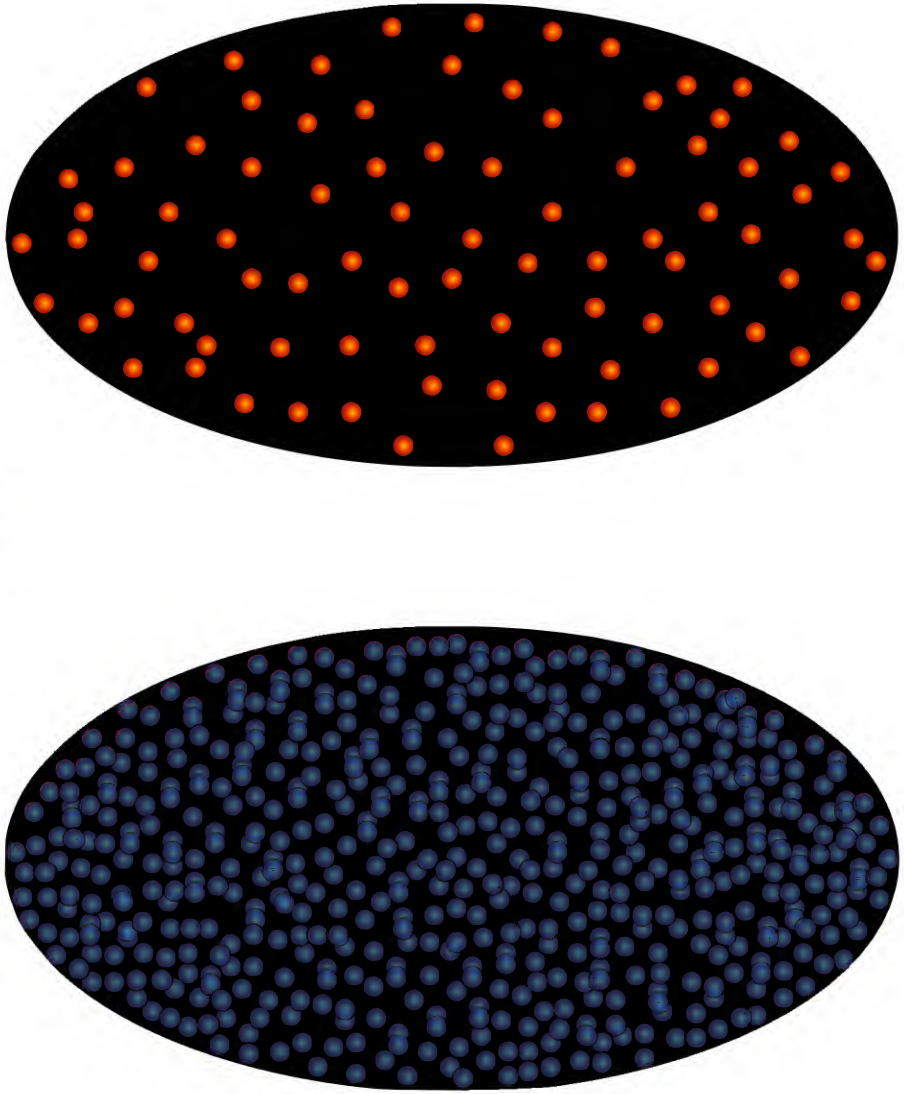






Anisotropy as a Function of Energy





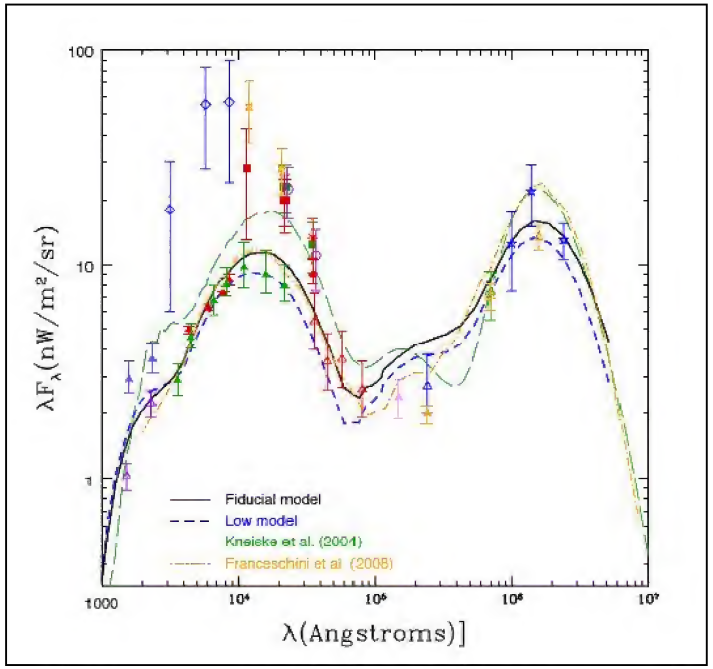
$$C_l^{\rm tot}(E) = f_{\rm bl}{}^2(E) C_l^{\rm bl} + f_{\rm gal}{}^2(E) C_l^{\rm gal}$$

VHE Gamma Rays in the EBL

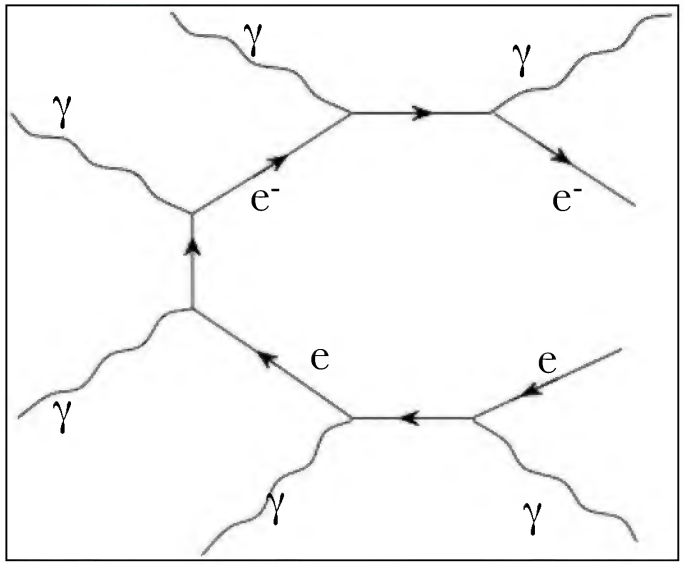
Extragalactic background light (EBL)

consists of:

- Emission from starlight at NIR/Opt./UV wavelengths
- Reradiated thermal dust emission at FIR wavelengths



Gilmore et al. 2009



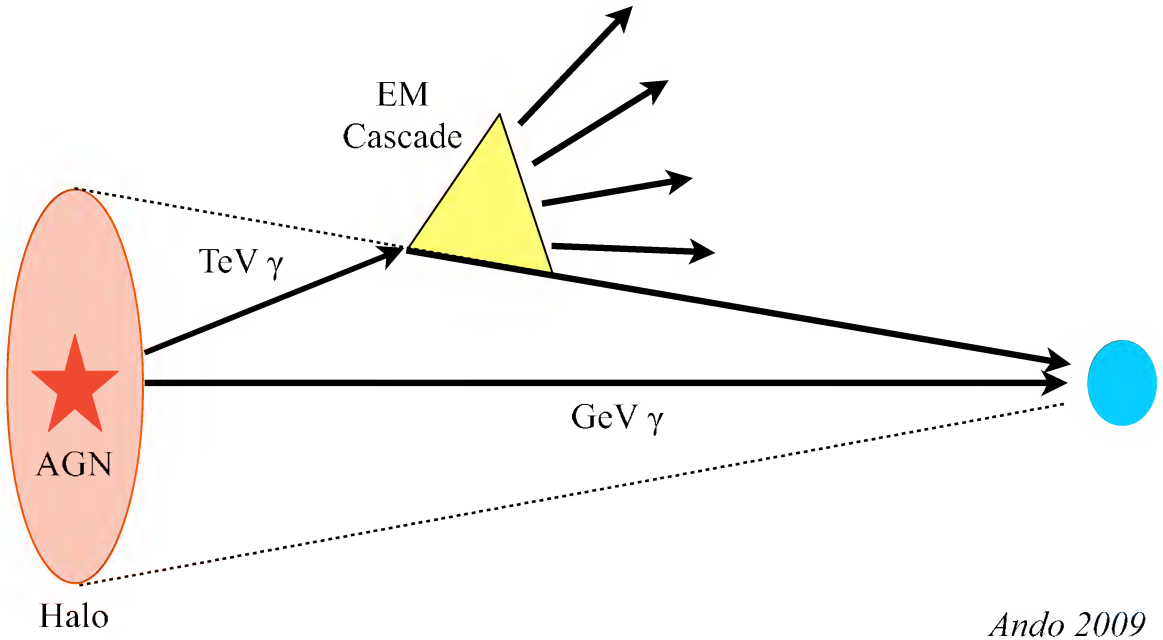
Venters 2009

Cascades -

- e^+e^- pair production
- inverse Compton scattering of cascade electrons

⇒ For a cosmological population - spectrum should exhibit a suppression at the high energy part of the EGRB and an enhancement at the lower energy part resulting from cascades

Magnetic Deflection of Cascades



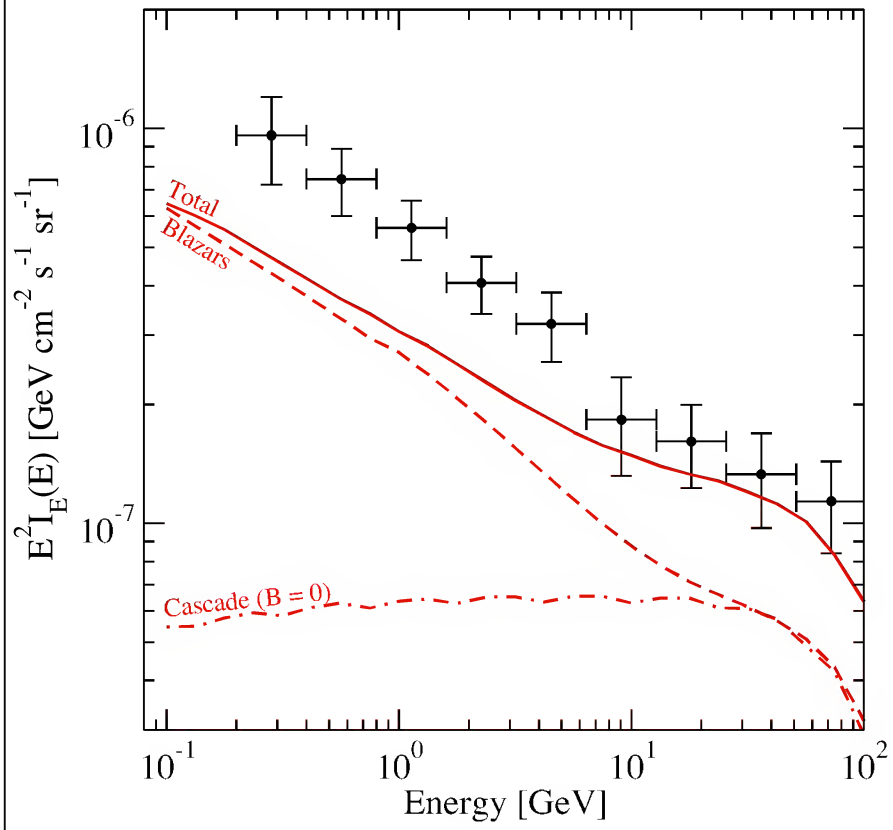
Ando 2009

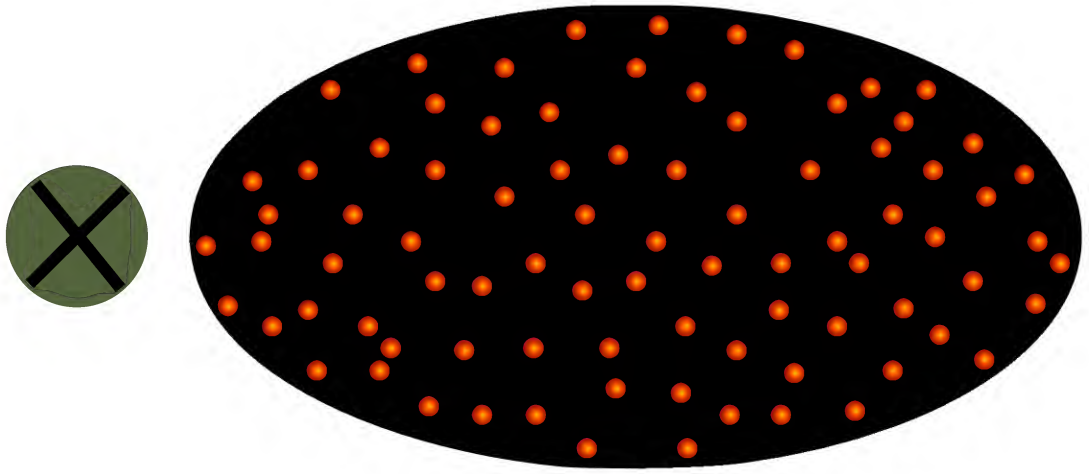
- Charged particles of cascades deflected by IGMF.
- Gamma-rays initially emitted off observer's line-of-sight initiate cascades that are deflected in direction of observer.
- Deflected emission makes a halo around source.

The Impact of Cascades

- Cascades impact the anisotropy energy spectrum of the EGB in three different ways:
  - For a population of emitters of VHE gamma-rays, cascades can comprise a significant fraction of the contribution of the parent population to the EGB ($I_{\rm par}(E)$).
  - Cascade radiation could be a significant contribution to the EGB at higher energies ($I_{\rm tot}(E)$)
  - Gamma-ray halos resulting from cascade development in the IGMF could impact the anisotropy of the parent population ($C_l^{(\rm n)}$).
- For our particular model, we considered IGMF field strengths that result in two limiting cases:
  - "Isotropization" of cascade radiation (strong IGMF - deflection of cascades is large enough that cascades from one source would be confused with another).
  - No magnetic deflection of cascades (zero IGMF).

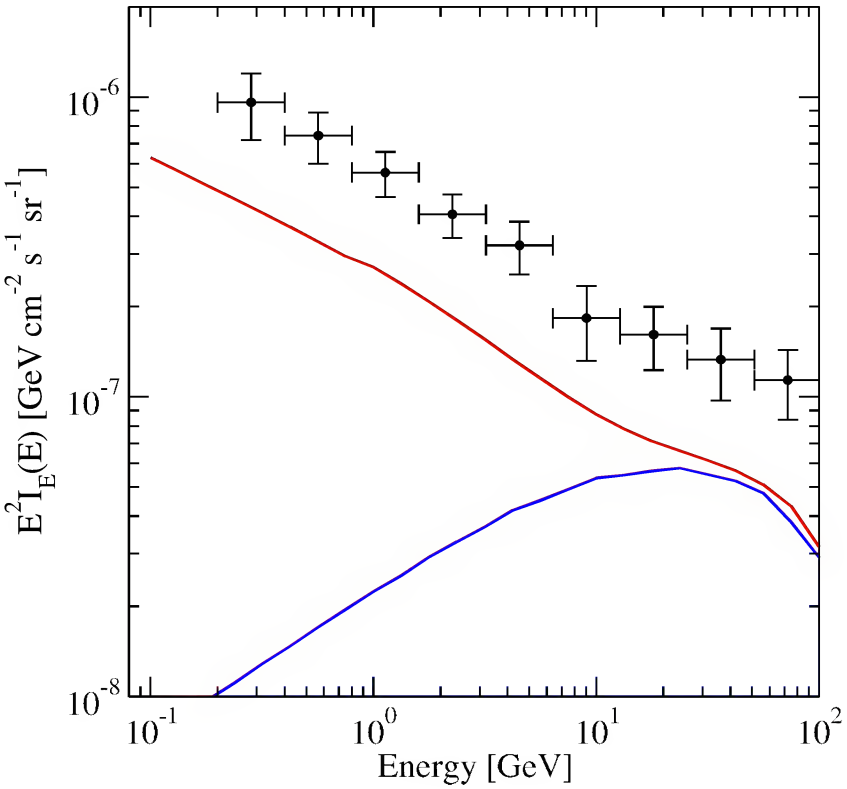
The Impact of Cascades (zero B)

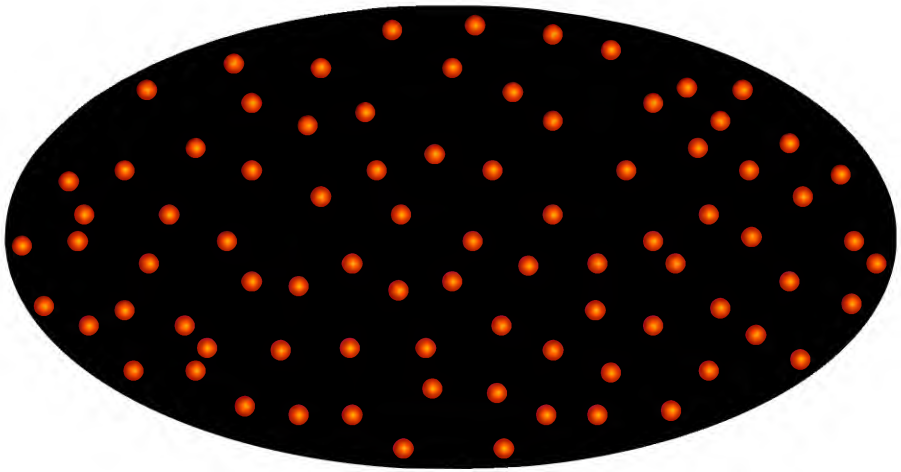


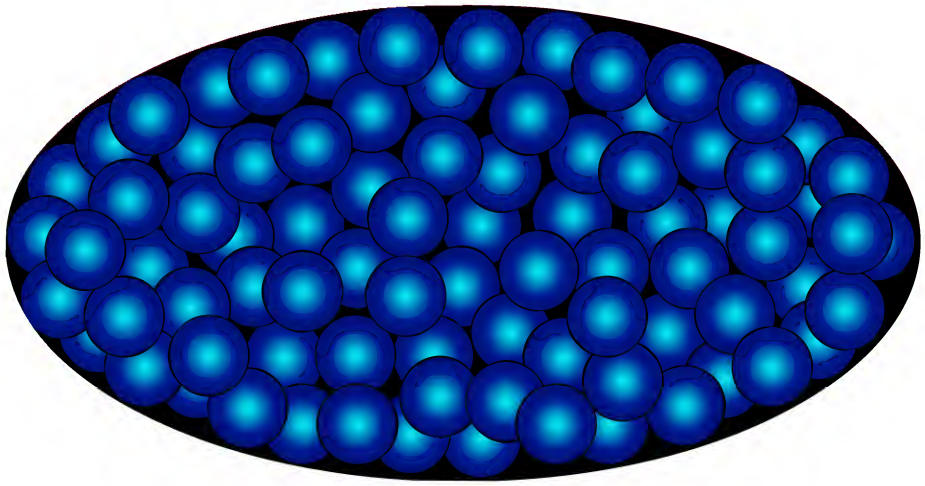


$$C_l^{\rm tot}(E) = (f_{\rm bl}(E) + f_{\rm cas}(E))^2 C_l^{\rm bl}$$

The Impact of Cascades (non-zero B)

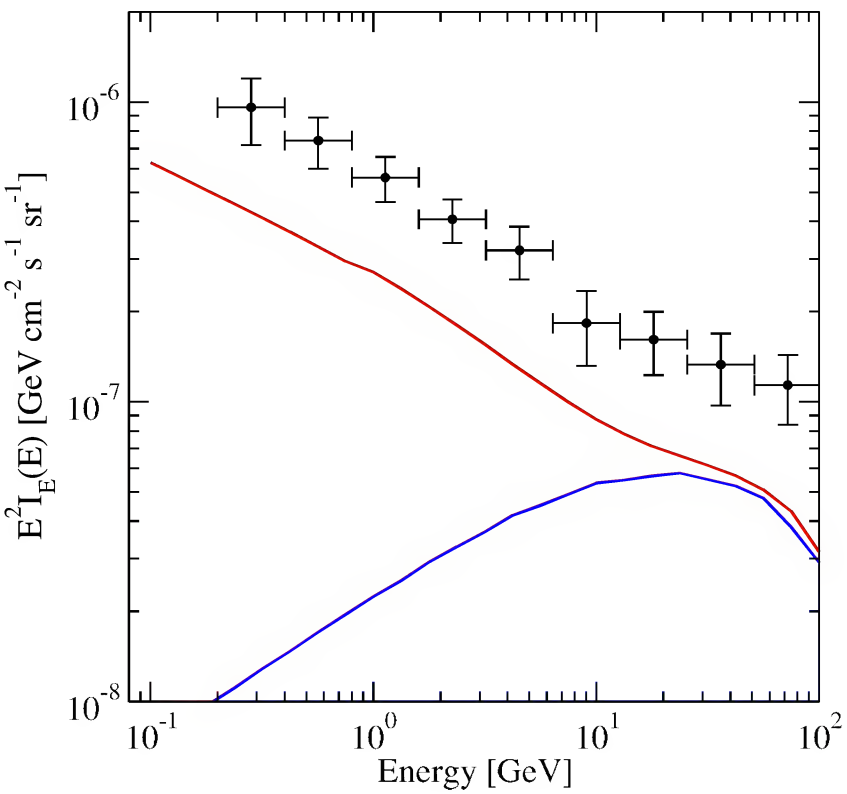


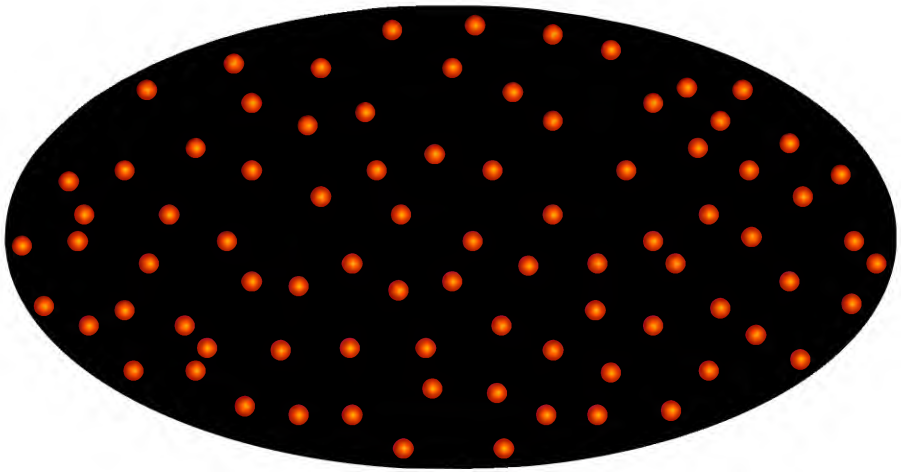


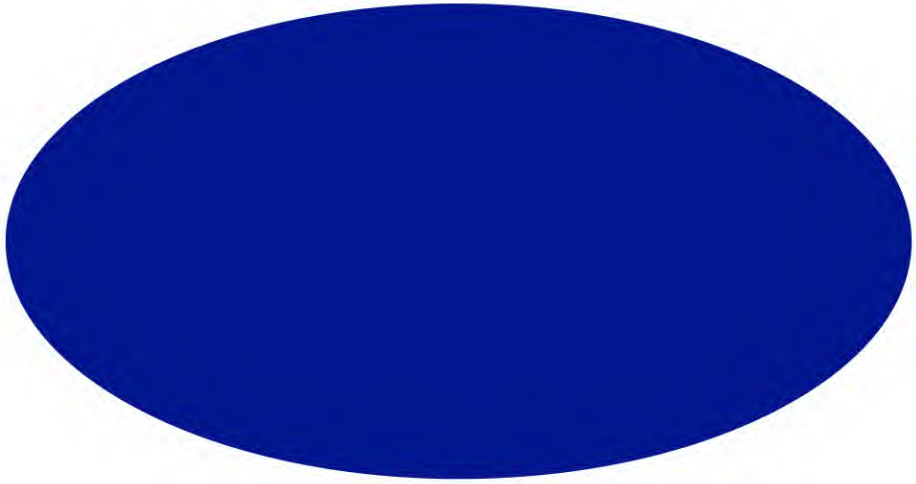


$$C_l^{\mathrm{tot}}(E) = f_{\mathrm{bl}}{}^2(E) C_l^{\mathrm{bl}} + f_{\mathrm{cas}}{}^2(E) C_l^{\mathrm{cas}} + \text{cross terms}$$

The Impact of Cascades (non-zero B)

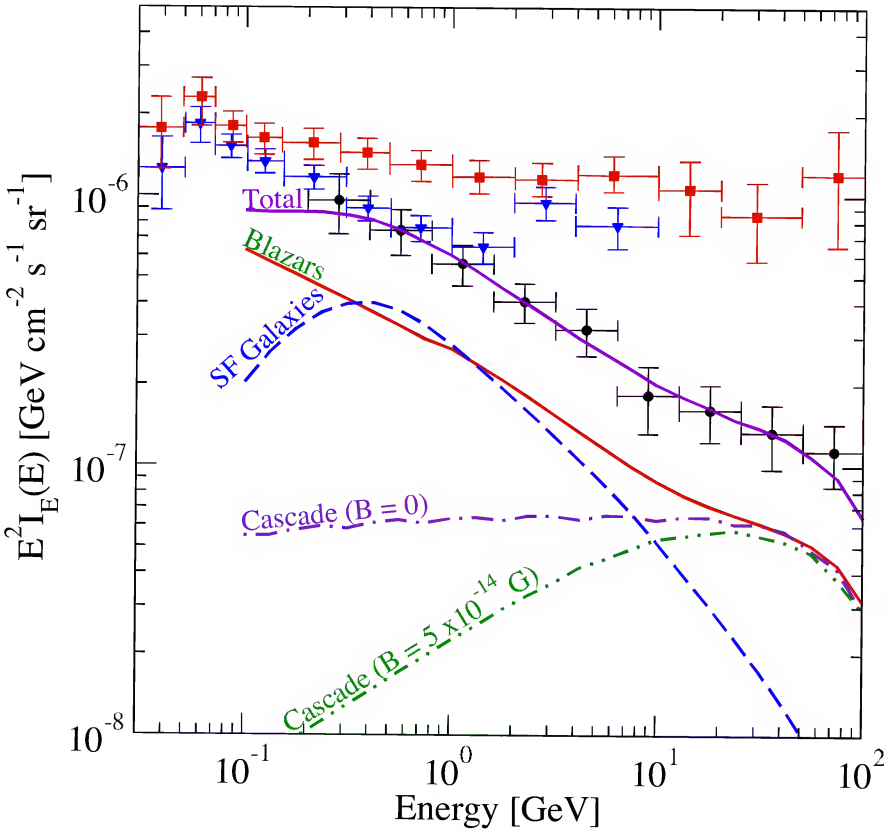


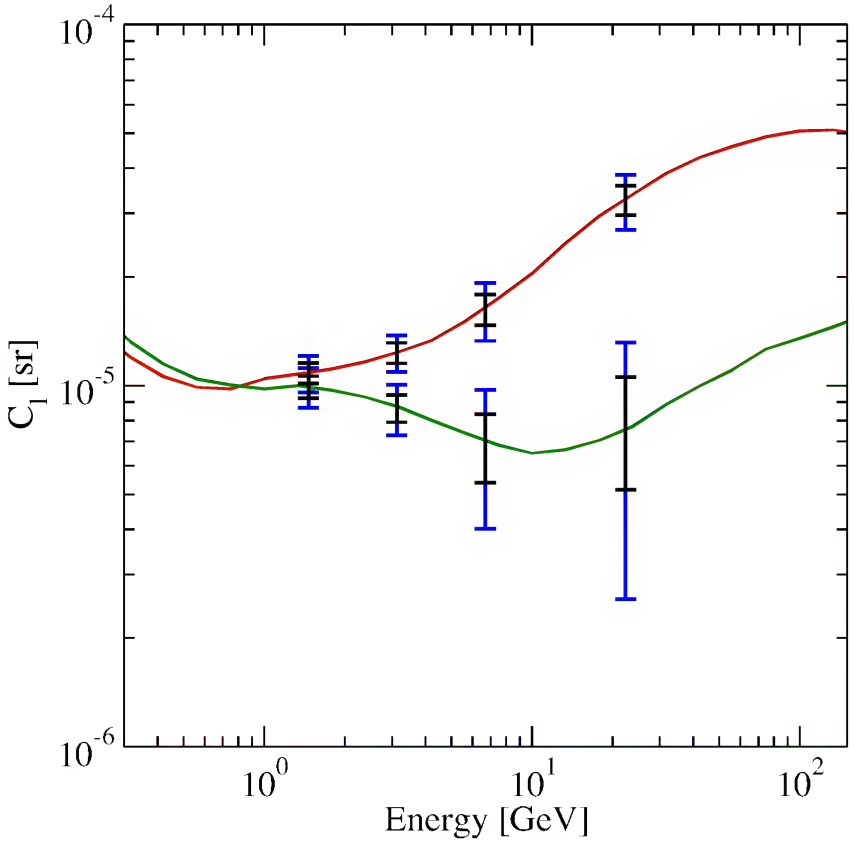


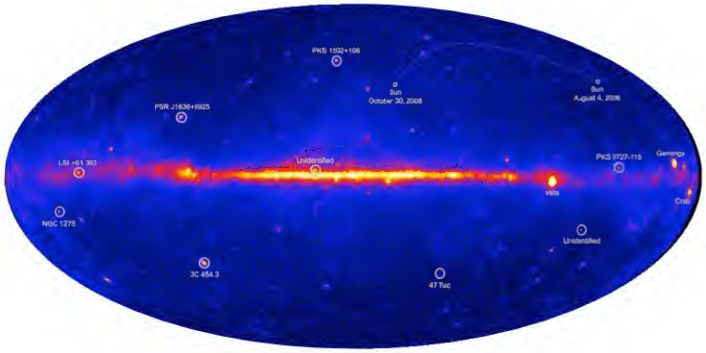


$$C_l^{\mathrm{tot}}(E) = f_{\mathrm{bl}}{}^2(E) C_l^{\mathrm{bl}} + \cancel{f_{\mathrm{cas}}{}^2(E) C_l^{\mathrm{cas}} + \text{cross terms}}$$

Cascades and EGB Anisotropy

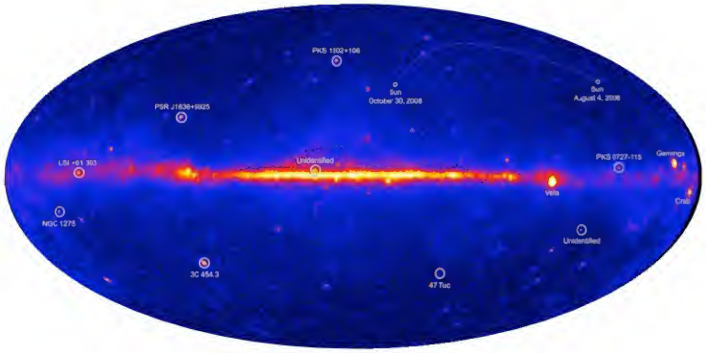






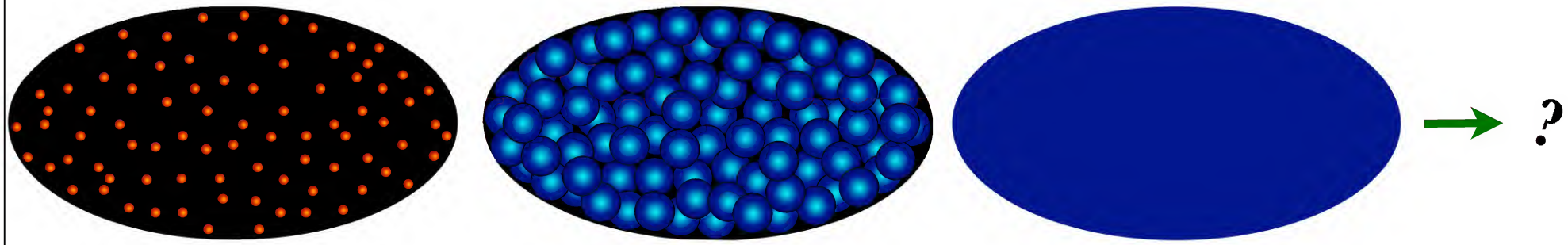
Future Work

- The cases presented here assume that the *cascades would not have appreciable anisotropy*, either because there are no halos (zero IGMF case) or the density of halos is large compared to the source density. For intermediate field strengths, cascades could have appreciable anisotropy, and their fluctuations would correlate with the parent population.
- To assess the impact of cascades and their corresponding halos on the observed gamma-ray sky, we will explore field configurations that more closely resemble those expected in large scale structure.

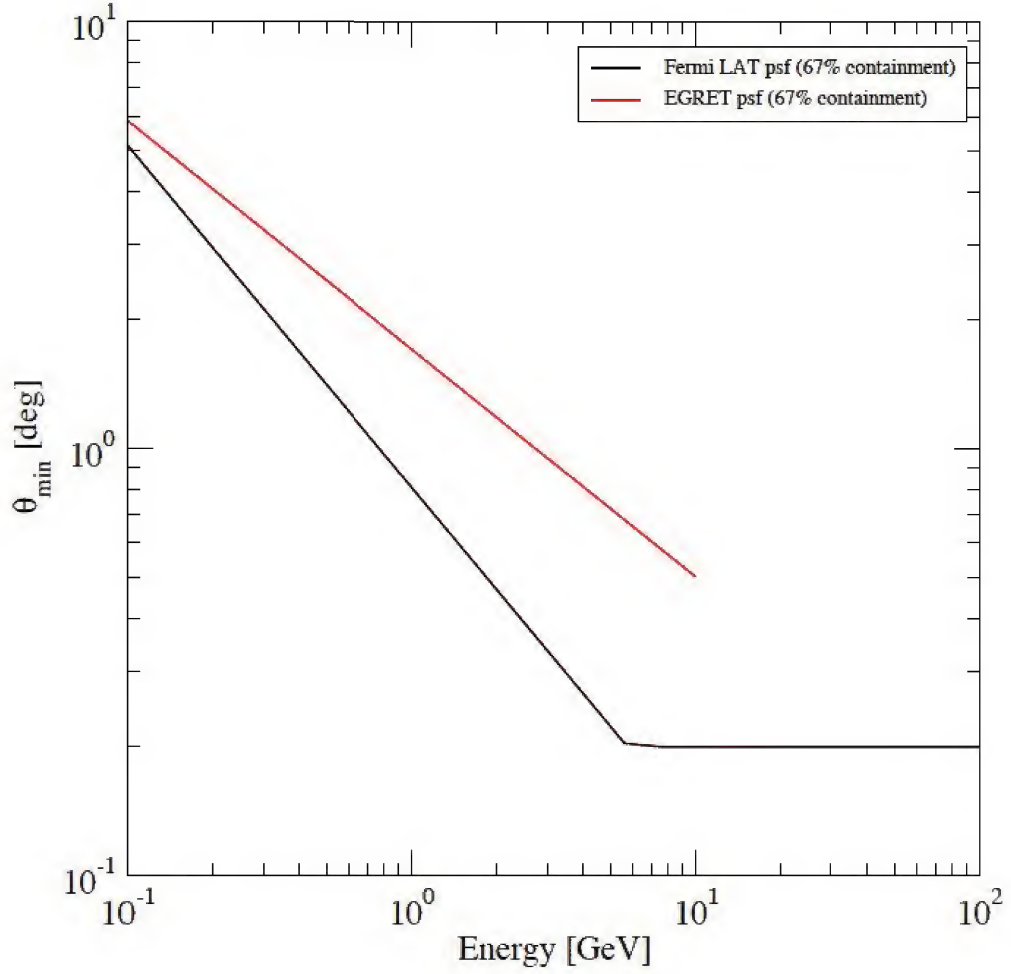


Conclusions

- As TeV gamma rays propagate through the extragalactic background light (EBL) and the CMB, they initiate electromagnetic cascades.
- Charged particles are deflected in the IGMF → halo of lower energy gamma rays around a TeV source → *modulation in the anisotropy in energy bands with significant cascade emission.*
- *Anisotropy studies of the gamma-ray sky could provide insight into the IGMF.*



Extra Slides


Fermi LAT psf (67% containment)
EGRET psf (67% containment)
θ_{min} [deg]
Energy [GeV]
10^{1}
10^{0}
10^{-1}
10^{-1}
10^{0}
10^{1}
10^{2}

PLASMA BEAM!!!

Yeah... Not really...